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CLOVERLEAF MICROGYROSCOPE WITH ELECTROSTATIC ALIGNMENT AND TUNING

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Government Interest

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 U.S.C. §202) in which the Contractor has elected to retain title.

Technical Field

The present invention relates to micro-machined electromechanical systems, and more particularly to a MEMS vibratory gyroscope having closed loop output.

Background Art

Micro-gyroscopes are used in many applications including, but not limited to, communications, control and navigation systems for both space and land applications. These highly specialized applications need high performance and cost effective micro-gyroscopes.

There is known in the art a micro-machined electromechanical vibratory gyroscope designed for micro-spacecraft applications. The gyroscope is explained and described in a technical paper entitled "Silicon Bulk Micro-machined Vibratory Gyroscope" presented in June, 1996 at the Solid State Sensors and Actuator Workshop in Hilton Head, South Carolina.

The prior art gyroscope has a resonator having a "cloverleaf" structure consisting of a rim, four silicon leaves, and four soft supports, or cantilevers, made from a single crystal silicon. A metal post is rigidly attached to the center of the resonator, in a plane perpendicular to the plane of the silicon leaves, and to a quartz base plate with a pattern of electrodes that coincides with the cloverleaf pattern of the silicon leaves. The electrodes include two drive electrodes and two sense electrodes.

The micro-gyroscope is electrostatically actuated and the sense electrodes capacitively detect Coriolis induced motions of the silicon leaves. The response of the gyroscope is inversely proportional to the resonant frequency and a low resonant frequency increases the responsivity of the device.

Micro-gyroscopes are subject to electrical interference that degrades performance with regard to drift and scale factor stability. Micro-gyroscopes often operate the drive and sense signals at the same frequency to allow for simple electronic circuits. However, the use of a common frequency for both functions allows the relatively powerful drive signal to inadvertently electrically couple to the relatively weak sense signal.

Residual mechanical imbalance of a cloverleaf micro-gyroscope results in misalignment or coupling of drive motion into the output axis. Presently, it is known to correct any misalignment of the mechanical modal axes by electronically rotating the sense and control axes into alignment with the mechanical axes.

However, electronic alignment, in which the sense and control axes are aligned with the mechanical modal axes results in second harmonics and electronic tuning, as by AGC phase adjustment, for example, has limited tuning range for high Q resonators and the tuning will change with variations in damping or temperature. It is known in the art that electrostatic tuning and AGC tuning operate by nulling quadrature amplitude. However, the quadrature amplitude signal more properly relates to misalignment so that when there is no misalignment, there is no quadrature signal, even though there may still be residual mistuning.

Summary Of The Invention

The present invention is a method for electrostatic alignment and tuning of a cloverleaf micro-gyroscope having closed loop operation. For closed loop output, a differential sense signal (S1-S2) is compensated by a

linear electronic filter and directly fed back by differentially changing the voltages on two drive electrodes (D1-D2) to rebalance Coriolis torque, suppress quadrature motion and increase the damping of the sense axis resonance. The resulting feedback signal is demodulated in phase with the drive axis signal (S1+S2) to produce a measure of the Coriolis force and, hence, the inertial rate input.

The micro-gyroscope and method of alignment and tuning of the present invention detects residual mechanical imbalance of the cloverleaf micro-gyroscope by quadrature signal amplitude and corrects the alignment to zero by means of an electrostatic bias adjustment rather than mechanical balancing. In-phase bias is also nulled by electronically coupling a component of drive axis torque into the output axis. Residual mistuning is detected by way of quadrature signal noise level, or a transfer function test signal and is corrected by means of an electrostatic bias adjustment. In the present invention, the quadrature amplitude is used as an indication of misalignment and quadrature noise level, or a test signal level, is used as a tuning indicator for electrostatic adjustment of tuning.

It is an object of the present invention to improve closed loop micro-gyroscope performance. It is another object of the present invention to improve the accuracy of micro-gyroscope alignment and tuning.

It is a further object of the present invention to provide electrostatic alignment and tuning for closed-loop operation of a vibratory micro-gyroscope. It is still a further object of the present invention to use the quadrature amplitude as an indication of misalignment. It is yet a further object of the present invention to use quadrature noise level or a test signal level as a tuning indicator. Yet a further object of the present invention is to provide independent control of alignment and tuning for a closed loop micro-gyroscope.

Other objects and features of the present invention will become apparent when viewed in light of the detailed description of the preferred embodiment when taken in conjunction with the attached drawings and appended claims.

Brief Description of the Drawings

FIGURE 1 is an exploded view of a prior art vibratory micro-gyroscope having four electrodes;

FIGURE 2 is a block diagram of a prior art closed-loop micro-gyroscope;

FIGURE 3 is an example of a prior art circuit schematic for closed loop sense/open loop drive operation;

FIGURE 4 is an exemplary electrode arrangement for the method of electrostatic alignment and tuning according to the present invention, the electrode arrangement includes eight electrodes; and

FIGURE 5 is a flowchart of the method for electrostatic alignment and tuning according to the present invention.

Best Mode(s) For Carrying Out The Invention

The method of the present invention is applicable to a closed loop micro-gyroscope. In the preferred embodiment, the closed loop micro-gyroscope is described in conjunction with Figures 1 through 3. For example purposes, and for simplicity, the closed loop control of the preferred embodiment will be described in accordance with a cloverleaf micro-gyroscope having four electrodes.

Figure 1 is an exploded view of the micro-gyroscope 10. The cloverleaf micro-gyroscope 10 has a post 12 attached to a resonator plate 14 having a cloverleaf shape with petals labeled 1, 2, 3, and 4. The cloverleaf resonator plate 14 is elastically suspended from an outer frame 16.

A set of four electrodes 18, located under the resonator plate 14, actuate the resonator plate and sense capacitance on the resonator plate 14. Drive electrodes D1 and D2 actuate movement of the resonator plate 14 and sense electrodes S1 and S2 sense capacitance. A set of axes are labeled x, y and z to describe the operation of the micro-gyroscope.

Rocking the post 12 about the x-axis actuates the micro-gyroscope 10. The rocking motion is accomplished by applying electrostatic forces to petals 1 and 4 by way of a voltage applied to the drive electrodes, D1 and D2. For a steady inertial rate, Ω, along the z-axis or input axis, there will be a displacement about the y-axis, or output axis, that can be sensed by the differential output of the sensing electrodes, S1-S2 or V_{thy}. The displacement about the y-axis is due to the influence of a rotation induced Coriolis force that needs to be restrained by a counteracting force.

Referring now to Figure 2, the wide-band closed-loop operation of the micro-gyroscope will be described. The closed-loop control circuit nulls displacement about the y-axis through linearized electrostatic torques. The electrostatic torques are proportional to control voltages. The two drive electrodes D1 and D2 produce linearized electrostatic torques about the x and y axes that are proportional to control voltages V_{tx} and V_{ty}. D1 and D2 are defined as:

$$D1 = V_o - V_{ty} + V_{tx}$$

and

$$D2 = V_o + V_{ty} + V_{tx}$$

where V_o is a bias voltage.

The linearized torques are defined as:

$$T_x = K_T V_{tx}$$

$$T_y = K_T V_{ty}$$

where the torque constant is:

$K_T = [2r_oC_oV_o][d_o]^{-1}$

r_o = offset from x or y axis to control, or drive, electrode center, C_o is the capacitance of one control electrode, V_o is the bias voltage, and d_o is electrode gap which is the nominal separation between the electrode plane and the resonator plane.

The control voltage V_{tx} provides for automatic gain control of the drive amplitude. The control voltage V_{ty} provides for Coriolis torque re-balance. The output axis (y-axis) gain and phase compensation are selected based on computed or measured transfer functions, G(s), from V_{ty} to V_{thy}. The reference signal used to demodulate V_{ty} is V_{thx} which is in phase with the drive axis rate signal, ω_x.

Referring still to Figure 2, the closed loop operation of the micro-gyroscope of the present invention measures the inertial rate, Ω, around the z-axis. Signals S1 and S2 are output from pre-amplifiers 20 that are attached to the sense electrodes S1 and S2.

The micro-gyroscope is set in motion by a drive loop 22 that causes the post to oscillate around the x-axis. The post rocks and has a rate of rotation about the x-axis. D1 and D2 apply voltages in phase therefore, they push and pull the resonator plate (not shown in Figure 2) creating a torque, T_x, on the x-axis.

When there is no inertial rate on the z-axis, there is no differential motion on S1 and S2. In this case, V_{thy} = S1-S2 = 0. S1 and S2 are in phase and indicate a rotation around the x-axis. V_{thx} = S1 + S2 is amplitude and gain phase compensated in an automatic gain control loop 22, 25, 27 to drive V_{thx} to V_{tx}. An amplitude reference level, V_r, is compared with a comparator 23 to the output of the amplitude detector 22 that determines the amplitude of V_{thx}. The resulting amplitude error is gain and phase compensated 25 and applied as a gain to an automatic gain control multiplier 27. A drive

voltage V_{tx} proportional to V_{thx} is thus determined that regulates the amplitude of the vibration drive.

When an inertial rate is applied, it creates a difference between S1 and S2 equal to V_{thy}. In the prior art V_{thy} was merely sensed open loop as being proportional to the rate of the micro-gyroscope. In the present invention V_{thy} is gain and phase compensated based on a computed, or measured, transfer function G(s). The resulting closed loop output voltage V_{ty} generates an electrostatic torque T_y to balance the Coriolis torque, thereby nulling the motion on the output axis.

To obtain the microgyroscope output signal, V_{out}, proportional to an input rate Ω, the rebalance torque voltage V_{ty} is demodulated with the drive reference signal V_{thx} by an output axis demodulator 29 and then processed through a demodulator and filter circuit 26. The DC component of the output signal of the demodulator, V_{out}, is proportional to the rotation rate Ω.

In the above-described closed loop control, if the drive axis creates a disturbance on the y-axis, it is also sensed using the above described demodulation scheme for the output. The closed loop operation prevents any rocking on the y-axis by feedback 24 applied by differentially feeding D1 and D2. D1 and D2 are responsive to V_{ty} as well as V_{tx}.

V_{thx} and V_{thy} are defined by:

V_{thx}=S1+S2

V_{thy}=S1-S2

Both V_{thx} and V_{thy} are directly proportional to the drive axis rate, i.e. $V_{thx} = K_\omega$ - ω_x and output axis rate, $\omega_x = K_\omega \Theta_x$ where K_ω is defined by:

$$K_\omega = [2r_o C_o V_o R][d_o]^{-1}$$

and R is the transimpedance from the preamplifiers 20.

The cloverleaves of the resonator plate and the substrate beneath S1 and S2 electrodes are well grounded at the drive frequency, capacitive drive feedthrough is reduced and stability margins are improved.

Figure 3 is an example of a schematic for closed loop sense/open loop drive operation. However, the present invention is applicable to either open loop or closed loop drive operation. It should be noted that in the configuration shown in Figure 3, the two sense signals S1 and S2 are differenced, filtered and amplified. The filter helps to remove residual second harmonics and adjusts loop phase to provide stable closed loop operation. The following amplifiers serve to combine the closed loop output feedback signal with the open loop drive signal providing the correct signals to electrodes D1 and D2. Rebalance of the Coriolis force and robust damping of the output axis resonance is provided by this wideband closed loop design.

The method of the present invention is best described herein with reference to an eight-electrode micro-gyroscope 100 shown in Figure 4. The closed loop control is very similar to that described in conjunction with Figures 1-3. However, in the micro-gyroscope having eight electrodes, there are obviously four additional electrodes, Q1, Q2, T1 and S3. D1 and D2 are used differentially for closed loop control on the y-axis and in common mode for x-axis control. S1 and S2 are dedicated to differential y-axis output sensing. S3 senses the motion of the drive, or x-axis, and T1 is used for tuning on x-axis. Q1 and Q2 are used to align the micro-gyroscope.

The micro-gyroscope has an inertia matrix J, a stiffness matrix, K and a damping matrix D which define the rotational motion about the x and y axes. In operation, the micro-gyroscope is driven about the x-axis in order to sense inertial rate about the z-axis through Coriolis coupling of the driven motion to the sense, or y, axis. As described above, in the preferred

embodiment of the present invention, the sense axis motion is nulled by a linear feedback torque u_y, where the torque is a measure of the inertial rate Ω.

It is also preferred that the micro-gyroscope have closely tuned operation. Closely tuned operation has a drive frequency that is selected close to the sense axis natural resonant frequency for maximum mechanical gain. Symmetrical design and accurate construction of the micro-gyroscope are important so that the two rocking mode natural frequencies are similar. A self-resonant drive about the x-axis, for example an AGC loop, will permit large drive motion with small torque controls.

It is not presently known how to fabricate a micro-gyroscope with atomic precision. Therefore, it is inevitable that asymmetry and imbalance in the matricies J, D, and K will lead to false Coriolis rate indications. The present invention independently controls alignment and tuning of the micro-gyroscope. Control torque, u_y, about the y-axis will be detected with zero inertial rate output.

The method 100 of the present invention is described with reference to Figure 5. Misalignment is detected 102 by the presence of a quadrature signal amplitude on V_{out}. The misalignment is corrected 104 by an electrostatic bias adjustment to electrode Q1 or Q2.

Residual mistuning is detected 108 and corrected 110 by way of an electrostatic bias adjustment to electrode T1. The detection 108 is accomplished by noting the presence of a quadrature signal noise level or a transfer function test signal.

In the following description of the present invention, the motion about the y-axis is regarded to be infinitesimal, i.e. perfect feedback, and drive axis motion about the x-axis is described as:

$$\vartheta_s = \vartheta_{xo}\sin(\omega_o t)$$

where ω_o is the operating frequency of the drive and ϑ_{xo} is the drive amplitude.

Small angle motion of a rocking mode gyroscope with inertia and stiffness misalignment is governed by:

$$\left(s^2\begin{bmatrix} J_{xx} & J_{xy} \\ J_{yx} & J_{yy} \end{bmatrix} + s\begin{bmatrix} D_{xx} & D_{xy} \\ D_{yx} & D_{yy} \end{bmatrix} + \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix}\right)\begin{bmatrix} \vartheta_x \\ \vartheta_y \end{bmatrix} = \begin{bmatrix} T_x \\ T_y \end{bmatrix}$$

where output axis torque $T_y = T_c+u_y+\delta_T T_d$. The Coriolis torque is $T_c = -J_{yy}2k\Omega s\vartheta_x$, k is the micro-gyroscope angular gain, the wideband control is $u_y=-G(s)(\vartheta_y+\delta_R\vartheta_x)$ and the drive torque $T_d=D_x s\vartheta_x$ is at a drive resonance of $\omega_o=(K_{xx}/J_{xx})^{1/2}$.

Analysis of the small motion on the y-axis is described hereinafter. The equation for y-axis motion has the form:

$$F(s)\vartheta_y+H(s)\vartheta_x = -G(s)\vartheta_y-G(s)\delta_R\vartheta_x+T_c(s)\vartheta_x+L(s))\delta_T\vartheta_x$$

$$\vartheta_y = \frac{-H(s)-G(s)\delta_R+L(s)\delta_T+T_c(s)}{F(s)+G(s)}\vartheta_x$$

$$u_y = -G(s)\vartheta_y-G(s)\delta_R\vartheta_x$$

$$u_y = \frac{G(s)H(s)+L(s)\delta_T+T_c(s)}{F(s)+G(s)}\vartheta_x+G(s)\left[\frac{G(s)\delta_R}{F(s)=G(s)}-\delta_R\right]\vartheta_x$$

$$u_y = \frac{-G(s)}{F(s)+G(s)}[-H(s)+L(s)\delta_T+T_c(s)+\delta_R F(s)]\vartheta_x$$

With properly compensated transimpedance buffers, electronic amplification and biased electrostatic drive (i.e., FIGURE 3), it is possible to provide loop compensation G(s) approximately equal to sK, so that u_y can be expanded as:

$$u_y = \frac{sK}{J_{yy}s^2 + (K + D_{yy})s + K_{yy}} [(J_{yx}-\delta_R J_{yy})s^2+(J_{yy}2k\Omega+D_{yx}-\delta_R D_{yy}-\delta_T D_{xx})s+(K_{yx}-\delta_R K_{yy})]\vartheta_x$$

$$u_y = \frac{1/(1+\delta_c)}{1 + \frac{J_{yy}s^2 + K_{yy}}{K(1+\delta_c)s}} \bullet \left[(J_{yy}2k\Omega + D_{yx} - \delta_R D_{yy} - \delta_T D_{xx}) + \frac{(J_{yx} - \delta_R J_{yy})s^2 + (K_{yx} - \delta_R s K_{yy})}{s} \right] s\vartheta_x$$

where $\delta_c = D_{yy}/K$. For steady state drive operation at $s=j\omega_o$, the feedback torque becomes:

$$u_Y = \frac{1/(1+\frac{D_{yy}}{K})}{1 + \frac{-J_{yy}\omega_o^2 + K_{yy}}{K(1+\delta_c)j\omega_o}} \bullet \left[(J_{yy}2k\Omega + D_{yx} - \delta_R D_{yy} - \delta_T D_{xx}) + \frac{-(J_{yx} - \delta_R J_{yy})\omega_o^2 + (K_{yx} - \delta_R K_{yy})}{j\omega_o} \right] j\omega_o\vartheta_x$$

which can be approximated as:

$u_y \approx (1-\delta_c)(1-j\varphi_c)(I_o+Q_o j)s\vartheta_x$

$u_y \approx (1-\delta_c)[(I_o+Q_o\varphi_c)+j(Q_o-I_o\varphi_c)]s\vartheta_x$

where $K=K_\omega K_c K_T$ can be set by compensator gain, K_c to achieve closed loop bandwidth, $\omega_c=K/J_{yy}/2=\omega_{OL}/\delta_c$, and open loop bandwidth, $\omega_{OL} = D_{yy} / J_{yy} / 2$

$\varphi_c = (J_{yy}\omega_o^2-K_{yy})/(K(1+\delta_c)\omega_o)$

$Q_o = -(-(J_{yx}-\delta_R J_{yy})\omega_o^2+(K_{yx}-\delta_R K_{yy}))/\omega_o$

$I_o = (J_{yy}2k\Omega+D_{yx}-\delta_R D_{yy}-\delta_T D_{xx})$

Demodulation of feedback voltage V_{ty}, which is proportional to u_y, with drive reference V_{thx} produces an output proportional to Ω plus an in-phase rate bias term due to the real component of u_y and is given by:

$$\Omega_{bi}=(D_{yx}-\delta_R D_{yy}-\delta_T D_{xx}+\varphi_c(-(J_{yx}-\delta_R J_{yy})\omega_o^2+(K_{yx}-\delta_R K_{yy}))/\omega_o)/2kJ_{yy}$$

Demodulation of feedback voltage V_{ty} with a signal in quadrature to V_{thx} produces a quadrature rate bias, which is given by:

$$\Omega_{bq} = (-\varphi_c(D_{yx}-\delta_R D_{yy}-\delta_T D_{xx})+(-(J_{yx}-\delta_R J_{yy})\omega_o^2+(K_{yx}-\delta_R K_{yy}))/\omega_o)/2kJ_{yy}$$

Given the above analysis of the small motion on the y-axis, the method of the present invention sets the sensor misalignment to zero, $\delta_R=0$ electronically, and then electrostatically aligns the microgyroscope by introducing an electrostatic cross coupling spring K^e_{xy} to cancel the misalignment torque. For example, $T_y = K^e_{xy}\vartheta_y = (J_{xy}\omega_y^2+K_{xy})\vartheta_y$. The remaining in-phase bias component of Ω_{bi} can also be nulled. This can be accomplished by introducing a relative gain mismatch $\delta_T\neq0$ on the automatic gain control voltage to each of the drive electrodes D1 and D2. This compensates for the false rate arising from finite modal damping and misalignment of the damping axes, i.e. set $D_{xy}-\delta D_{xx}=0$. The compensation also applies to any systematic changes in damping affecting both axes, for example, as may be caused by bulk temperature changes.

For a four-electrode cloverleaf micro-gyroscope like the one shown in Figure 1, the cross-coupled electrostatic stiffness can be introduced by applying more or less bias voltage to one of the drive electrodes, D1 or D2. The in-phase rate bias error is also nulled as described above.

In the preferred closed loop operation of the present invention, the compensation is set such that G(s)=sK and K is maximized to be consistent with loop stability. In such a case, dependence on scale factor and phase shift

on the mechanical response are minimized. Furthermore, with fully tuned operation,

$$\omega_{nx}^2 = K_{xx}/J_{xx} = \omega_{ny}^2 K_{yy}/J_{yy} = \omega_o^2$$

and there is no closed loop phase error, $\varphi_c=0$. For tuned conditions, maximum mechanical gain and maximum loop gain occur. Therefore, noise due to input electronic noise is minimized.

For an eight-electrode design, as shown in Figure 4, electrostatic cross-coupled stiffness, K^e_{xy} for alignment purposes can be introduced by modification of the bias voltage of either Q1 or Q2. Electrostatic modification of net K_{xx} for tuning purposes can be accomplished by increasing or decreasing the bias voltage T1 as well.

For example, if $\omega_{nx}>\omega_{ny}$ then the bias voltage applied to T1 is made larger than the voltage applied to S1 and S2. The total stiffness is the elastic stiffness plus the electrostatic stiffness. The total stiffness about the x-axis is lowered so that ω_{nx} is also lowered and brought into tune with ω_{ny}. In this regard, the present invention provides a tuning method for vibratory micro-gyroscopes in which one of the bias voltages is increased or decreased until a minimum value of the rms noise is obtained or until a transfer function indicates tuning. In the alternative, a test signal may be maximized.

For the eight-electrode design, a bias on Q1 or Q2 will introduce cross axis electrostatic stiffness. To align the gyroscope, Q1 bias is adjusted until the quadrature amplitude is nulled. δ_T is adjusted until the rate output is nulled.

To independently tune the micro-gyroscope according to the present invention, the electrostatic tuning bias, electrode T1, is adjusted until closed loop quadrature or in-phase noise, or another tuning signal, is minimized.

While particular embodiments of the present invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art. Accordingly, it is intended that the invention be limited only in terms of the appended claims.